Implementing a Strategy for Mars Exopaleontology

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In exploring for a record of ancient Martian life, the goals, methods, and assumptions differ substantially from those required in exploring for extant life. To differentiate this activity from the conventional discipline of exobiology, the exploration of ancient extraterrestrial life is referred to as exopaleontology. The practical task facing exopaleontology is to define a strategy for exploring Mars' fossil record during the decade-long exploration program that lies ahead. Consideration of the quality of paleontological information preserved under different geological conditions is important in order to develop a strategy with broad applicability. To help guide site selection during the Mars Global Surveyor (MGS) Program, a site-selection strategy for exopaleontology—based on microbial fossilization processes in a variety of extreme environments regarded to be good analogs for early Earth and Mars—was developed.

The microbial fossil record encompasses a wide range of information, including cellular remains (organic-walled, permineralized replacements, and external molds of cells), trace fossils (microborings in rocks), biofabrics (micro-textural features of sediments attributed to the behavior of microorganisms), stromatolites (finely laminated biosedimentary structures), biominerals (biomediated mineral precipitates), and chemofossils (biomarker organic compounds, isotopic and trace-element signatures). The preservation of fossils is strongly influenced by the physical, chemical, and biological factors of the environment, which together ultimately determine the kinds of information that will be captured and retained in the rock record. In detrital sedimentary systems, preservation is favored by rapid burial in fine-grained, clay-rich sediments. In chemical sedimentary systems, preservation is enhanced by rapid entombment in fine-grained chemical precipitates. For long-term preservation, host rocks must be composed of stable minerals that resist chemical weathering and that form an impermeable matrix and closed chemical system capable of protecting biosignatures from extensive alteration during subsequent diagenetic changes or metamorphism. In this context, host rocks composed of highly ordered, chemically stable mineral phases, like silica or phosphate, are especially favored. Such lithologies tend to have very long crustal residence times and (along with carbonates and shales) are the most common host rocks for the Precambrian microfossil record on Earth. An important goal in implementing the strategy for Mars exopaleontology is the discovery of surface exposures of these and related minerals during upcoming Mars missions. Efforts continue to define high-priority sites for exopaleontology using Viking data, but site priorities will be refined in the future as new data are incorporated from the Mars '96 Global Surveyor orbiter (beginning in March 1999). Present emphasis is on locating sites that are likely to have sustained long-lived aqueous sedimentation. This approach has identified a large number of potential sites for exopaleontology.

A critical step in implementing a strategy for exploring for evidence of past or present Martian life and prebiotic chemistry is to locate accessible surface outcrops of aqueously formed mineral deposits of the type known to be good long-term repositories for microbial fossil information in the Precambrian rock record on Earth. One limitation is a lack of high spatial resolution remote-sensing data at wavelengths that can provide information about surface mineralogy. The thermal emission spectrometer, which is presently in orbit at Mars, will obtain a global map of surface mineralogy at a spatial resolution of ~3 kilometers per pixel during its nominal mission. But to optimize the selection of sites for a sample return in 2005 and beyond will require infrared mapping at a spatial resolution capable of resolving individual outcrops. Results from ongoing analog remote-sensing studies in the Great Basin of western North America indicate that a resolution capability of about 100 to 300 meters per pixel will likely be needed to precisely locate sedimentary deposits of the right mineralogy (i.e., rock types most favorable for preserving a fossil record of past life) in order to effectively plan rover operations. The 2001 MGS orbiter is presently slated to carry a high-resolution, mid-infrared mapping spectrometer called THEMIS which will be capable of attaining this resolution at selected high priority sites.

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Molecular Biomarkers in Living Stromatolites

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Stromatolites, among the most common fossils in the geologic record, are defined as organo-sedimentary structures formed by sediment trapping and binding or by mineral precipitation (or both) of microbial communities living in shallow water environments. The microfossil record in stromatolites traces Earth's history since the oldest life, over 3.5 billion years ago. During most of this time, microbial life has dominated Earth, and has been responsible for transforming the primitive anaerobic environments of early Earth, devoid of free molecular oxygen, to the modern aerobic world that supports contemporary biology. Microbial mats are "living" stromatolites, modern day analogs that provide an opportunity (a window to the past) to study the way ancient microbial communities lived and evolved. Today, a variety of these "living" analogs, representing a range of environmental and organismal parameters, are available for study throughout the world. For the most part, the dominate members of recent mats are oxygenic photosynthetic bacteria, the cyanobacteria. The evolution of oxygen-producing photosynthesis within the cyanobacteria heralded the beginnings of our modern aerobic world, and the timing of this event is of particular interest in attempts to understand the process of Earth's evolution.

A variety of stable organic compounds, generally referred to as chemical fossils or biomarkers, have been extracted from stromatolites. Indigenous fossil biomarkers can provide clues to the identity of the original mat-building community and provide insights into the paleoenvironment in which this community existed. The challenge is to understand the link between such molecular fossils and their "living" counterparts, the biomarker molecules synthesized by contemporary mat-building bacteria, and then to apply this information to the study of contemporary microbial mats. Efforts at Ames Research Center are focused on a type of columnar (or conical) stromatolite, the Conophyton, which is one of the most distinctive groups of Precambrian stromatolites. A "living" Conophyton analog is currently forming as the result of silicification of a mat constructed by a fine filamentous cyano-bacterium called *Phormidium* in hot springs located in Yellowstone National Park.

The study began by isolating a variety of *Phormidium* cyanobacteria from columnar, microbial mats found in Yellowstone. Two important types of organic molecules have been identified in these cyanobacteria: a group of branched alkanes having 17 to 20 carbons (C_{17}–C_{20}), and hopanoids, a highly cyclized C_{30} molecule (see figure). Both methylalkanes and hopanes are excellent biomarkers for cyanobacteria, are resistant to biodegradation, and are presently known to be the oldest biomarkers dating to Proterozoic rocks 1.7 billion years old. Interest at Ames is in the processes involved in the deposition or degradation of organic material during early mineralization of microbial mats, particularly as this relates to the potential for preserving biomarkers such as branched alkanes and hopanes, which are thought to be more highly resistant to microbial degradation.

In order to relate biomarker analysis of *Phormidium* cultures to their natural environment, the study at Ames is concerned with a type of submerged, columnar *Phormidium* mat widely prevalent in the terraced pools found in the Midway Geyser Basin in Yellowstone. As the pools dry up, the mat surface is gradually covered with a silica layer.